How do front/rear wing modifications correlate with competitive success in the 2024 Formula One Season?

Word Count: 4500

1. Introduction

In motorsport engineering, aerodynamics governs the interaction between air and a vehicle in motion, shaping the forces that influence grip, stability, and speed. Two core aerodynamic forces—downforce and drag—are at the heart of this relationship. Downforce increases the vertical load on the tires, enhancing cornering and braking capabilities without adding physical mass, while drag resists the vehicle's forward motion, reducing top speed. Race car design thus demands a delicate balance between maximizing downforce and minimizing drag, a trade-off that defines competitive success in Formula One (Weingart, 2015).

This challenge is further complicated by phenomena such as ground effect, where airflow beneath the car creates a low-pressure zone, effectively "sucking" the vehicle toward the road. Exploiting ground effect can yield substantial gains in downforce without a proportional drag penalty, but it also introduces sensitivity to track surface variations and car ride height (McCabe, 2005). Complementing underbody aerodynamics are the front and rear wings, which act as airfoils to shape airflow, manage turbulent wakes, and generate aerodynamic loads critical for handling performance.

The front wing, being the car's first point of contact with air, plays a dual role: generating downforce and redirecting airflow toward key downstream components like the floor and diffuser. Rear wings, meanwhile, stabilize the car at high speeds and through corners, and their performance is enhanced by mechanisms such as the Drag Reduction System (DRS), which reduces drag on straights to improve overtaking ability (Jackson, 2018).

Despite these well-established principles, few publicly available studies quantify how wing designs—especially the configuration and behavior of front and rear wings—translate into on-track performance over an entire Formula One season. Proprietary data and limited transparency have left a critical gap in empirical season-long assessments of aerodynamic influence.

This research addresses that void by analyzing front and rear wing performance across the 2024 Formula One season. Using a hybrid methodology that combines content analysis of race footage with a custom data visualization tool, this study evaluates key metrics including wing behavior,

sector time changes, tire degradation, and slipstream effectiveness. The goal is to correlate aerodynamic setup decisions with measurable performance outcomes—providing insight into how design philosophies affect competitive success.

Ultimately, this paper not only bridges a methodological gap in motorsport literature, but also offers a new framework for studying season-wide aerodynamic trends. Through this lens, McLaren's 2024 Constructors' Championship win is analyzed not just as a sporting triumph but as an aerodynamic achievement.

2. Literature Review

Evolution of Aerodynamic Understanding in Motorsport

Aerodynamics has long been a cornerstone of motorsport engineering, and its study has evolved dramatically over the decades. In the foundational work by McCabe (2005), the history of aerodynamic principles in motorsports was traced from a rudimentary understanding of lift and drag to their strategic applications in high-speed racing. McCabe emphasized the critical role of downforce, not just as a stabilizing force but as a strategic lever to improve cornering and traction. He documented how innovations like inverted wing profiles, streamlined fairings, and eventually ground effect technologies marked turning points in Formula One (F1), elevating aerodynamics from an auxiliary discipline to a central tenet of vehicle design.

The emergence of computational tools further accelerated this evolution. Aljure et al. (2018) demonstrated how wall-modeled large eddy simulations (WMLES) could provide detailed insight into unsteady aerodynamic phenomena, drastically reducing computational cost without sacrificing accuracy. Their research underscored the increasing reliance on high-fidelity simulations in modern racing environments, validating historical theory with empirical results. The integration of turbulence-resolving models has enabled engineers to simulate turbulent wake interactions between cars, a critical factor in slipstream behavior and overtaking feasibility.

This progress marks a broader trend: Motorsport aerodynamics has shifted from wind tunnel-based experimentation to a simulation-driven environment. Computational Fluid Dynamics (CFD) enables rapid iteration on thousands of wing geometries and body profiles before physical testing begins. This transformation has made aerodynamic development more accessible to teams with diverse resources, narrowing performance gaps and intensifying competition.

Fundamental Aerodynamic Principles in Racing

At its core, motorsport aerodynamics revolves around managing two opposing forces: downforce and drag. While downforce enhances traction and stability during high-speed cornering, it typically introduces drag, reducing straight-line speed. The goal of any aerodynamic package is thus to maximize the former while minimizing the latter. Race engineers and aerodynamicists often face a trade-off: increased downforce improves handling but compromises top speed, while a drag-reducing setup risks reduced grip in corners.

Weingart (2015) explored this balancing act through on-track validation of CFD simulations for a Formula SAE vehicle. His work demonstrated how parameters like wing angle of attack and camber influence lift and drag, reinforcing the importance of multi-element wings in creating adaptable aerodynamic responses. His emphasis on the center of pressure was particularly significant, a dynamic point where the net aerodynamic force acts. Maintaining its stability across speed ranges is critical to handling predictability. A sudden shift in the center of pressure can unsettle the vehicle, especially during high-speed transitions between corners or under braking.

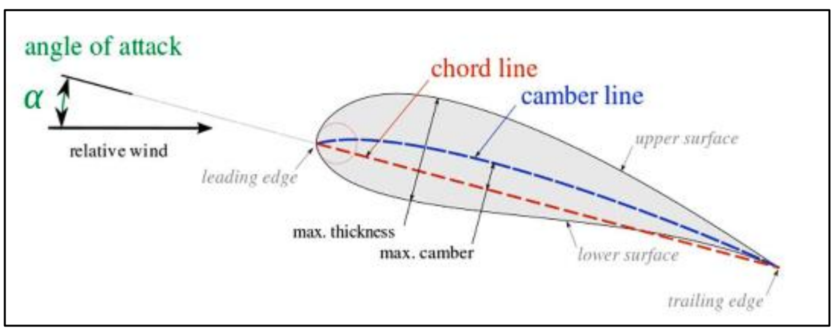

Figure 1: Descriptive rear wing angle of attack. Taken from Weingart (2015)

The concept of ground effect—a phenomenon where airflow beneath the vehicle creates a low-pressure zone to “suck” the car to the ground—was another milestone in racing design as visually noted in Figure 2. Roberts (2017) expanded on this by investigating boundary-layer transition phenomena on wings operating in ground effect. His experiments showed that ignoring laminar-

turbulent transitions could significantly misrepresent aerodynamic forces, especially in Formula One, where small changes in ground clearance can produce dramatic shifts in performance. Roberts' findings emphasized the non-linear behavior of underbody aerodynamics and the necessity of incorporating transitional flow models to predict vehicle behavior under real-world conditions.

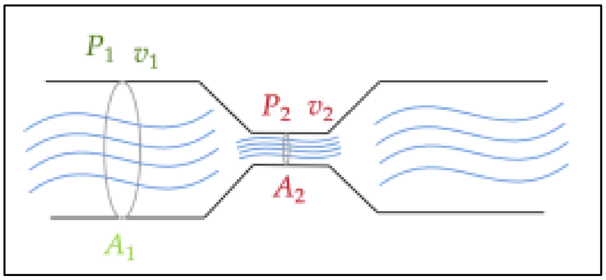

Figure 2: Visual representation of the Venturi effect. License CC Durán (2022).

Another fundamental consideration is vortex generation and control. Vortices are used to energize boundary layers and manage turbulent wakes, especially around high-drag elements like open wheels. These vortex structures, though inherently unstable, can be harnessed through precise geometrical tuning of winglets and endplates. This technique is used extensively in F1 to guide airflow toward critical regions such as the bargeboards, diffuser, and brake ducts.

Formula 1-Specific Aerodynamics

Formula One, the pinnacle of motorsport engineering, takes aerodynamic complexity to its apex. In this realm, front and rear wing designs are meticulously tuned to create a well-balanced aerodynamic envelope, delivering optimal handling, minimal drag, and adaptability to diverse track layouts and weather conditions.

Front Wing Design and Function: As the first component to engage incoming airflow, the front wing serves a dual function. It must generate downforce while also shaping airflow downstream toward the bargeboards, sidepods, floor and rear wing. Patil et al. (2014) and Roberts (2017) noted that

modern F1 front wings rely heavily on vortex generation to manage tire wake and energize flow to sensitive areas like the diffuser. Adjustability, particularly in angle of attack and element positioning, allows teams to fine-tune balance based on track conditions. These wings often feature up to five elements, each contributing to both local downforce and downstream airflow conditioning. Front wing performance is particularly sensitive to yaw angles, which vary during cornering and can induce asymmetric airflow and handling imbalances if not properly accounted for.

The importance of tire wake management also cannot be overstated. The front wing's endplates are sculpted not just for strength, but to create outwash or in-wash vortex structures that control how airflow interacts with the rotating front tires—one of the largest sources of drag and turbulence on an F1 car. Any deviation in this carefully orchestrated airflow, caused by debris, damage, or improper setup, can cascade through the vehicle's aerodynamic package.

Rear Wing Design and Function: Rear wings are primarily tasked with generating rear-end downforce, stabilizing the car at high speeds, and through corners. Jackson (2018) emphasized the transformative role of the Drag Reduction System (DRS), which allows parts of the wing to open under certain conditions, reducing drag and increasing top speed. His CFD analysis showed that with DRS, top speeds improved by over 37% with real-world telemetry (Figure 3). This balance of drag reduction and downforce recovery underscores the rear wing's importance. Additionally, beam wings and endplate slits help reduce vortical losses and improve flow reattachment, further boosting efficiency.

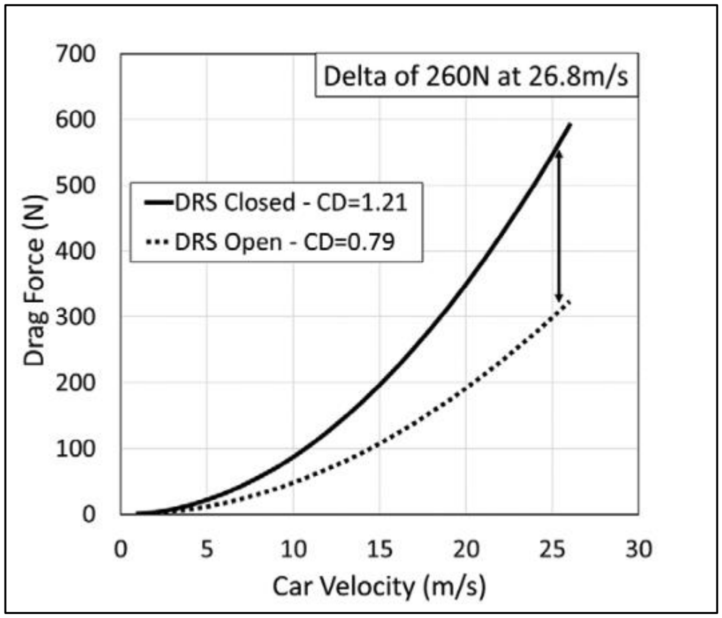

Figure 3: Comparison of drag force with DRS open and closed. Taken from Jackson (2018).

The design of rear wings also reflects track-specific trade-offs. At circuits like Monza (Italy), teams bring “skinny” wings with reduced surface area to cut drag. In contrast, Monaco or Hungary demand maximum downforce, achieved through large wing profiles and steep angles. The ability to rapidly swap and tune rear wing configurations is thus vital to race performance.


Figures 4 and 5: McLaren’s Monza reduced surface area wing vs. Hungary’s steep angle wing. Taken from MotorsportF1 under Creative Commons.

Regulatory Framework: Regulations significantly shape wing design. The FIA (international motorsports governing body) imposes strict geometric, positional, and functional constraints to promote safety, reduce costs, and ensure competitive parity. As Sing et al. (2023) demonstrated through their use of genetic algorithms for aerodynamic optimization, even within rigid regulatory bounds, innovative solutions can be found to enhance performance. These constraints have pushed teams to exploit legal gray areas—using flexible materials, hidden slots, or fluidic creative problem-solving, making aerodynamic development a game of both engineering and interpretation.

Recent Developments in F1 Aerodynamics (2016-2023)

Recent years have seen exponential growth in both computational methods and aerodynamic strategies. Tienphuc et al. (2016) provided valuable contributions by simulating flow fields around generic F1 geometries using advanced turbulence models. Their work highlighted the importance of accurately capturing wake dynamics, particularly behind the diffuser and rear wind. Their simulations were able to resolve complex trailing vortices, enabling better predictions of vehicle drag and rear-end stability.

Roberts (2017) further contributed to the findings of Tienphuc et. Al (2016) by incorporating laminar-turbulent transitions in ground-effect studies, revealing how neglecting this flow behavior can lead to underestimating or overestimating drag and lift coefficients. His use of transition-sensitive turbulence models marked a significant step forward in simulating real-world conditions. In circuits with aggressive elevation changes, like Spa-Francorchamps, this level of precision becomes essential to maintaining aerodynamic consistency.

Bombardieri et al. (2020) shifted focus toward structural-aerodynamic integration by implanting an aero-structural optimization, where wing deflection and aerodynamic loading are co-simulated, showing that performance gains could be realized not just from shaping airflow but also from

managing structural flexibility. In modern F1, where carbon-fiber wings deform slightly under load, accounting for this deformation can yield better predictive models of real-world performance.

Additionally, Vishwanath et al. (2022) explored the topology of floor and body interactions under transient conditions. Their findings emphasized that transient instabilities—such as changes in yaw and pitch—affect underfloor airflow much more severely than previously modeled. Their results reinforce the necessity of robust aero setups that maintain performance under variable conditions, such as braking zones, curbs, and close-following situations.

Research Gap

Despite the vast body of research dedicated to aerodynamic theory, simulation techniques, and component-level optimization, there remains a noticeable gap in the literature explicitly connecting aerodynamic wing design to season-wide competitive outcomes. Much of the existing research, while rigorous and technically insightful, tends to isolate aerodynamic phenomena under controlled or idealized conditions. Studies such as those by Tienphuc et al. (2016), Roberts (2017), and Singh et al. (2023) provide a deep insight into the behavior of aerodynamic components or offer novel optimization techniques. Still, they rarely bridge the gap between design intent and measurable race-day success throughout a championship season.

One noticeable limitation in the field is the lack of studies examining how specific front and rear wing configurations, adjusted track-to-track, correlate with real-world metrics such as podium finishes, sector time differentials, tire degradation rates, or overtaking efficiency. While Jackson (2018) made strides in validating DRS functionality with telemetry, few have attempted to evaluate how front and rear wing changes affect a team's consistency or trajectory in the Constructors' standings (team championship). The absence of this broader linkage creates a disconnect between component-level performance and team-wide success indicators.

Additionally, existing analyses often focus on static or single-event snapshots rather than dynamic, season-long patterns. Modern F1 seasons are characterized by constant development; teams introduce incremental wing updates across different circuits to adapt to drag/downforce trade-offs. However, there is a scarcity of research tracking these modifications and evaluating their outcomes in a longitudinal framework. The result is a research landscape rich in theory and simulation, but relatively thin in applied, performance-oriented synthesis.

This paper aims to address this void by systematically analyzing front and rear wing design strategies across the 2024 FIA Formula One season, correlating these choices with quantifiable team performances. By integrating race footage coding and performance statistics, the research seeks to connect the aerodynamic architecture of F1 vehicles to their championship outcomes. This approach moves beyond CFD results and isolated component testing, offering instead a holistic assessment of how aerodynamic decisions manifest in competitive success. In doing so, this study hopes to contribute a new perspective to the field: one where form, function, and final results are studied not in isolation but in continual interaction of the most competitive motorsport calendar in the world.

3. Methodology

Given the proprietary nature of aerodynamic data within Formula One and being in the final year of the Ground Effect cars (2022-2025), where teams guard simulation results and component designs as competitive assets, direct access to full CFD models or real-time wind tunnel data is virtually nonexistent for independent researchers. As such, this study adopts a content analysis approach, focusing on publicly observable aerodynamic configurations and correlating them with publicly available performance data. This methodology allows for the systematic collection and interpretation of visual, numerical, and performance-based data from each Grand Prix during the 2024 season.

The decision to use content analysis stems from the reality that Formula One teams treat aerodynamic data as classified intellectual property. Detailed CFD simulations, track-specific setup sheets, and aerodynamic component iterations are not released to the public. Consequently, alternative approaches such as firsthand telemetry analysis or access to wind tunnel performance metrics were deemed infeasible. Content analysis offers a feasible and robust alternative by capturing consistent patterns from broadcast footage, official photographs, and post-race technical briefings.

A coding sheet was designed for use across every 2024 race weekend to ensure consistency and minimize observer bias. This sheet includes fields for observed front and rear wing specifications, presence of DRS-specific elements, track characteristics (classified as high or low downforce), and performance outcomes including qualifying position, finishing position, tire degradation patterns (Figure 6 and Figure 7), and overtaking instances. A standardized framework, along with a coding partner, ensures that data collected across circuits remains comparable. The data collection protocol emphasizes reproducibility, with cross-referencing from multiple ootage sources (F1 TV, team YouTube debriefs, and technical analysis articles).

Figure 6: Low tire degradation.
CC from Autosport

Figure 7: High tire degradation.
CC from F1 Dictionary

This qualitative-quantitative hybrid method leverages the consistency of race weekend formats to structure observations, enabling researchers to link wing choices directly to situational performance without access to confidential telemetry or wind tunnel data.

Data Sources

This study utilized three primary types of data: technical specifications, race performance metrics, and team standings. Together, these elements create a multi-dimensional dataset capable of supporting correlation-based analysis.

1. Technical Specifications: Data on front and rear wing configurations were collected using visual inspection from high-definition race footage, pre-race garage footage, and technical post-race interviews. Observable indicators included:
    a. Bends on the front and rear wings on corner entry and exit.
    b. Number of wing elements.
    c. DRS slot presence and deployment.
    d. Wing angle relative to the car.

Photographic references were archived for each race weekend to ensure data reliability and enable repeated analysis. In some cases, race briefing or paddock analysis by experts such as Craig Scarborough were used to supplement direct observations.

2. Race Performance Metrics: Performance outcomes were quantified using the following parameters:
    a. Qualifying position.
    b. Final race position.
    c. Fastest lap delta (relative to median lap)
    d. Number of overtakes completed
    e. Tire degradation (1 = Low, 2 = Medium, 3 = High)
    f. Sector-specific time gains or losses

These were sourced from FIA post-race reports, the official F1 data portal, and third-party analytics services such as Motorsports Stats. This structured approach allowed for meaningful comparison between wing configurations and their impact on real-time race dynamics.

3. Team Standings and Championship Trends: A team's placement in the Constructors' Championship served as a macro-level success indicator. Points accumulation across races was charted and overlaid with the aerodynamic configuration patterns logged via content analysis. This allowed for season-wide performance visualization, which was critical in identifying whether certain design philosophies translated into consistent success.

To track intra-season developments, each team's wing design evolution was also recorded. For example, McLaren's mid-season switch to higher downforce rear wings in high-degradation circuits was tracked alongside a notable uptick in podium finishes. Similarly, Red Bull's preference for minimal front wing angles at power circuits like Monza was cross-checked against overtaking frequency and tire wear data.

Analysis Framework

The analysis centered around identifying correlations between front and rear wing configurations and success metrics across the 2024 season. These success metrics were defined using both race-specific and season-wide indicators:

- Race Specific Metrics:
  - Overtake success rate
  - Average time gained per sector (under similar fuel and tire loads)
  - Tire longevity (stint lengths)
- Season-Wide Metrics:
  - Total points accumulated

- Average finishing position
- Frequency of podium finishes
- DNFs (did not finish) or poor finishes due to balance/stability issues

Although the study did not establish formal causal relationships due to observational nature, strong correlation patterns were analyzed, suggesting a strategic aerodynamic advantage. For example, McLaren's increased use of rear wing designs on high-downforce tracks was repeatedly associated with their best race finishes and enhanced tire longevity. In contrast, Ferrari's dependence on low-drag configurations sometimes correlated with better metrics but resulted in rear-end instability, as demonstrated in Monaco and Hungary. When various wing configurations were employed during a single race weekend (such as different setups among drivers), intra-team comparisons were conducted. This approach controlled for factors like engine power and pit strategy, allowing the aerodynamic configuration to emerge as a primary differentiator.

Coding Sheet and Data Extrapolation

To support the analysis and reduce manual data handling, a custom Python-based GUI tool was developed using the Tkinter library. This interface allowed for efficient input of coded observations from each race event, which were saved into a structured CSV format. The GUI (as shown on Figure 8) included entry fields for each coded parameter, such as front wing issue severity (0-2), rear wing behavior rating (0-3), DRS deployment (binary), sector time change, overtaking attempts, tire degradation (1-3), and slipstream effectiveness (1-3). Once the data was entered, the interface provided functionality to export to Excel and generate dynamic visualizations.

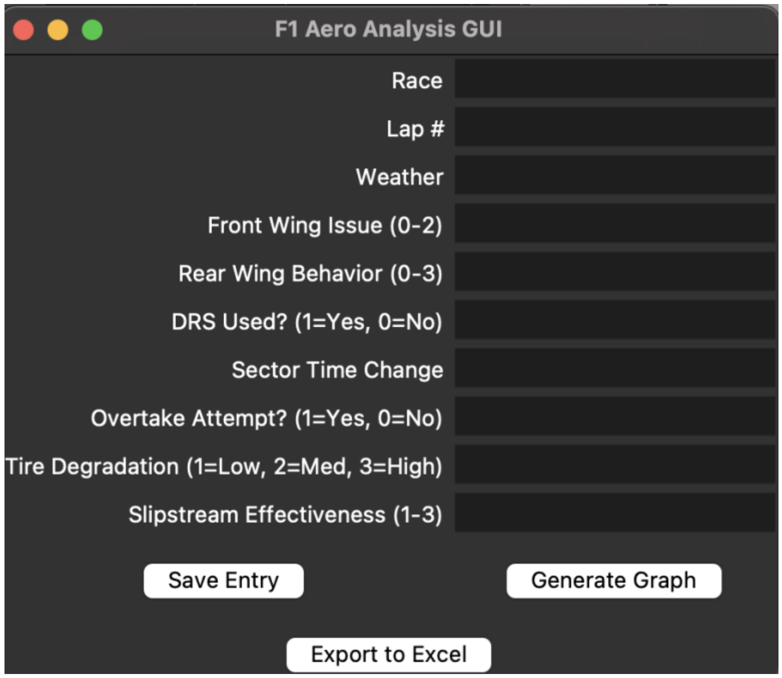

Figure 8: GUI interface of coding sheet tracker in Python

The visualization component relied on Matplotlib and Seaborn to generate density plots and average value comparisons across races. By plotting average metric values across multiple races and teams, the tool facilitated rapid identification of trends, such as the relationship between rear wing behavior and tire degradation, or the consistency of sector time gains under specific aerodynamic setups.

Quantifying qualitative visual observations required thoughtful encoding from both me and my coding partner. For example:

- Front Wing Issue (0-2): 0 for clean, stable behavior; 1 for minor instability or vibration; 2 for visible aero failure, understeer symptoms, and sparks generated by hitting the track.
- Rear Wing Behavior (0-3): 0 for stable flow, 1 for minor oscillation, 2 for repeated instability, 3 for major instability or balance loss

- Slipstream Effectiveness (1-3): Evaluated based on car gain in straight-line following another car; 1 for no effect, 2 for moderate gain, 3 for strong effect enabling overtaking.

This numerical transformation allowed the qualitative data (gathered from race footage and analysis) to be used in quantitative correlation. The standardization ensured consistency across multiple data entry points, and the resulting graphs allowed immediate visual comparison between teams, tracks, and aerodynamic philosophies. Thus, the Python program not only streamlined the content analysis process but also allowed for iterative visualization, reducing the risk of data misinterpretation and significantly enhancing the methodological rigor of this season-wide analysis.

Given the specificity of this research—linking aerodynamic wing configurations to real-world performance across an entire season—there were no existing platforms or tools available that met the unique demands of this project. Most race analysis tools are either proprietary to Formula One teams or are geared toward fan engagement, lacking the granularity required for academic evaluation. Developing a unique application was therefore necessary to ensure precise, customizable data handling.

The replicability of this approach has been built into the tool's architecture. The Python script is modular,with clearly defined functions for data entry, validation, storage, and visualization. Future researchers or analysts can adapt the fields to include different metrics, expand to additional seasons, or even apply the same framework to other forms of motorsport. All components—from GUI interaction to data visualization—are annotated for clarity and publicly shareable upon request, supporting open-source research principles and encouraging further validation or extension of this work.

Limitations

Despite the structured approach, this methodology carries inherent limitations:

- Visual inference risk: Certain aerodynamic features (e.g., underfloor shaping, beam wing configurations) are difficult to quantify without physical access or CAD models.
- Confounding factors: Elements such as weather, pit strategy, and driver error can obscure aero-performance correlations.
- Subjectivity in content analysis: While the coding sheet aims to standardize data collection, some interpretive variability remains between both myself and my coding partner.

4. **Results**

Observed Wing Design Trends

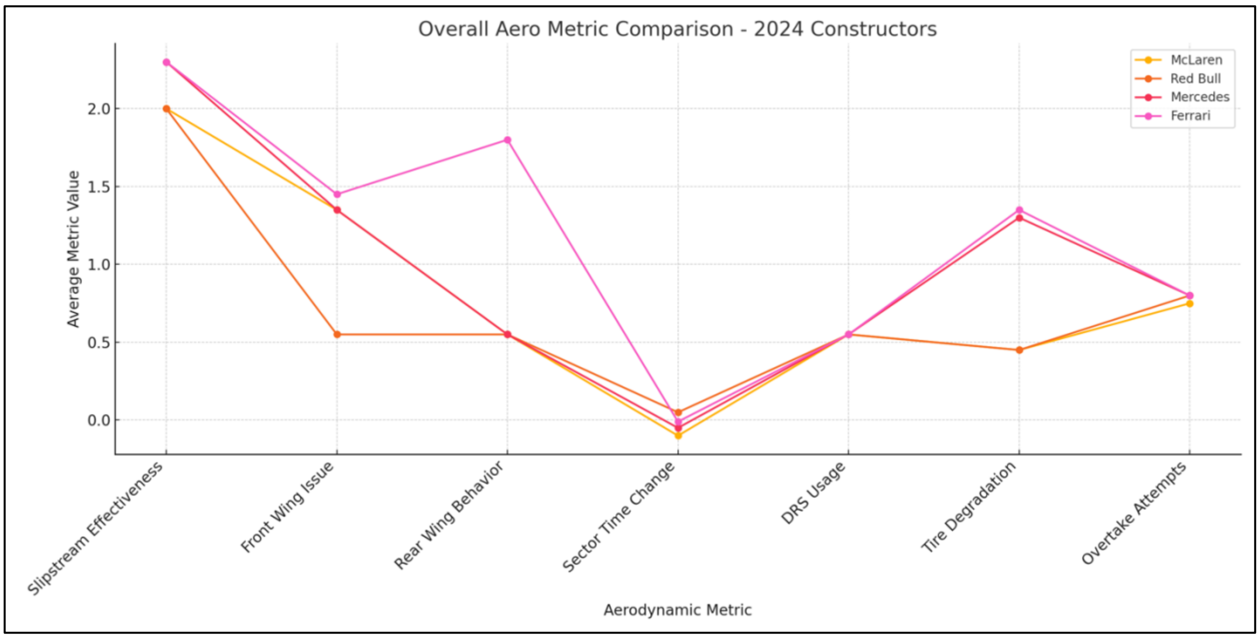

Figure 9: Data of teams that consistently finished in positions 1 – 5 in races.

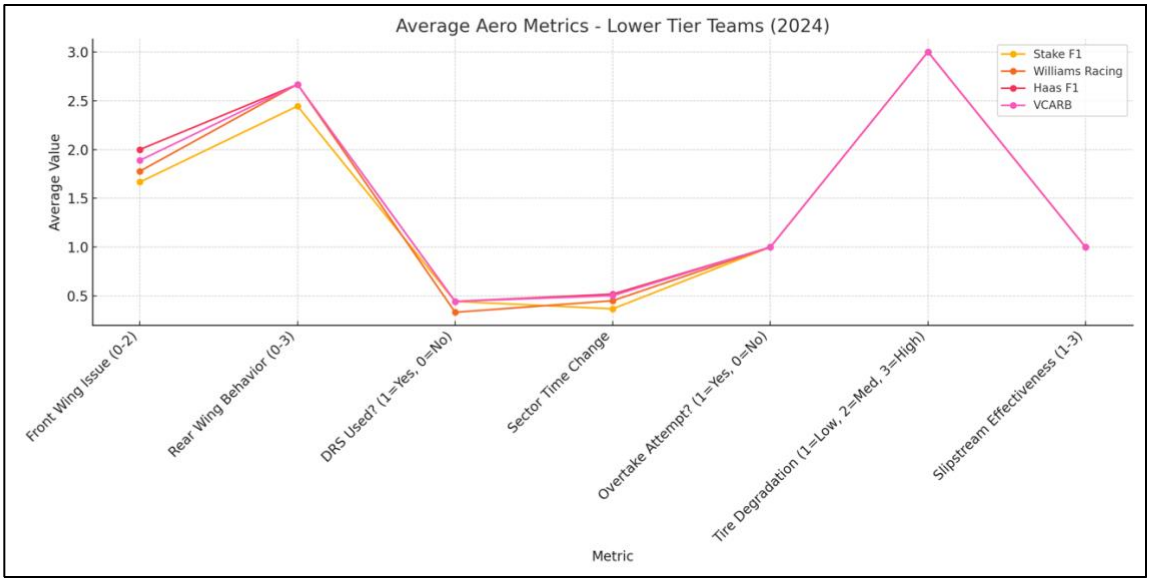

Figure 10: Data of teams that consistently had DNFs or positions 11 – 20.

5. **Discussion**

Interpretation of Findings

The visual data in Figures 9 and 10 clearly illustrate the aerodynamic disparity between top-tier and lower-tier teams in the 2024 Formula One season. McLaren and Red Bull, in particular, showcased aerodynamic consistency through low front and rear wing instability metrics. These values aligned closely with low sector time changes, suggesting superior aerodynamic balance and load distribution—factors that directly contribute to pace retention over a race stint.

These findings align well with previous literature. For example, Weingart (2015) stressed the importance of pressure center stability for handling predictability. Teams like Ferrari and Haas, which displayed higher rear wing instability, corroborate his analysis with more frequent sector time losses and greater tire degradation. Similarly, Roberts' (2017) emphasis on boundary-layer transition complexity in ground-effect environments was echoed in how lower teams suffered from

inconsistent slipstream performance—implying airflow detachment issues under variable track conditions.

Unexpectedly, Mercedes—while considered a top team—showed sector time patterns and tire degradation closer to those of Ferrari. This suggests that while their aerodynamic concepts may be sound in theory, real-world applications (possibly hindered by driver feedback or mechanical setup) limited their performance gains.

Moreover, DRS effectiveness diverged significantly. Red Bull maintained high DRS deployment and slipstream effectiveness, often converting these into overtaking opportunities. On the contrary, lower-tier teams showed lower values across both metrics, reinforcing that aero efficiency, particularly in drag reduction and airflow recovery, is crucial to race-day competitiveness.

Limitations of Findings

While these results highlight critical performance relationships, several limitations must be acknowledged. The foremost constraint is the inaccessibility of technical data. Without proprietary telemetry, CFD models, or wind tunnel reports, all aerodynamic assessments were based on visual interpretation, expert commentary, and observable race footage.

Additionally, the absence of strict control variables, such as equal weather conditions, mechanical setups, or pit strategies, makes it difficult to isolate aerodynamics as the sole performance driver. For example, tire degradation may be influenced by suspension settings, not just aerodynamic balance.

Furthermore, this study does not claim causation. While strong correlations were observed between aero stability and performance, confounding factors (driver skill, strategy calls, etc.) mean we cannot definitively attribute performance outcomes solely to aerodynamic configuration. Instead, this work demonstrates the strength of aero design as a predictive and complementary performance factor.

Implications

The results carry several meaningful implications. First, teams should prioritize aerodynamic stability—not just downforce levels—when designing wings. A high-downforce but unstable wing (as seen in Haas and Stake F1) often results in poor real-world performance. Second, track-specific aero modularity (as demonstrated by McLaren) offers competitive advantage by maintaining efficiency across circuits with different demands.

Strategically, teams must invest in rear wing oscillation control and DRS tuning. Improved aero balance enables better tire life, which in turn opens up flexible race strategies—an important advantage under the current tire degradation-heavy era. At a regulatory level, findings here may prompt the FIA to further scrutinize how budget limitations hinder aero evolution for smaller teams. If parity is a goal, broader wind tunnel/testing allocations or standardized wing elements for non-works teams could be explored.

6. **Conclusion**

This study investigated the aerodynamic behavior of Formula One teams throughout the 2024 season, with a specific focus on front and rear wing configurations and their correlation with competitive performance. Using a custom Python-based tool and a content analysis framework, the research provided quantifiable insights into how wing design impacts lap times, tire degradation, and overtaking opportunities. Key findings indicate that teams with lower wing instability, higher slipstream effectiveness, and adaptive rear wing usage consistently outperformed others across multiple metrics. McLaren emerged as the most balanced in both aero setup and race execution, supporting the notion that stable, well-integrated aero design is foundational to modern F1 success. Based on the data analyzed across wing behavior, tire degradation, and sector timing, McLaren's aerodynamic superiority was consistently evident throughout the season. This conclusion is reinforced by real-world outcomes, as McLaren ultimately secured the Constructors' Championship in 2024. This

work fills a notable research gap by offering a season-wide, component-specific, and statistically supported account of how aerodynamic choices influence real-world outcomes. It contributes a novel methodological approach to motorsport engineering—one that can be replicated, refined, and expanded across future seasons or motorsport categories. Future research could incorporate onboard telemetry data (if available), CFD snapshots, or even wind tunnel replicas for more granular aerodynamic mapping. Longitudinal studies across regulation eras would also help trace design evolution and strategic shifts. Ultimately, this analysis reaffirms what engineers and strategists intuitively know: that in a sport of milliseconds, aerodynamic discipline is not just a differentiator—it is a determinant.

References

Aljure, D. E., Meneghini, J. R., Ferrari, A., & Sander, D. M. (2018). Wall-modeled large eddy simulations of flow over multiple vehicles in close proximity. Journal of Fluids and Structures, 84, 399–420. https://doi.org/10.1016/j.jfluidstructs.2018.01.002

Autosport. (2024). F1 tyre saving: What is it, why is it important, and how is it done? https://www.autosport.com/f1/news/f1-tyre-saving-what-why-how-is-it-done/10535074/

Bombardieri, C. (2020). Wing shape optimization for a Formula One front wing using a CFD-based genetic algorithm [Master's thesis, Politecnico di Milano].

Fédération Internationale de l'Automobile. (n.d.). Technical Regulations. https://www.fia.com/regulation/category/110

Formula1-Dictionary. (n.d.). Using tires. https://www.formula1-dictionary.net/using_tires.html

Hearst Media. (n.d.). Chase Elliott turn 4 practice image [Photograph]. https://hips.hearstapps.com/hmg-prod/images/chase-elliott-enters-turn-4-on-the-apron-during-practice-news-photo-1739726234.pjpeg

Jackson, F. F. (2018). Aerodynamic optimisation of Formula Student vehicle using computational fluid dynamics [Master's thesis, Oxford Brookes University]. ORA - Oxford University Research Archive.

LinkedIn. (n.d.). Article cover image – CFD tools in racing [Image]. https://media.licdn.com/dms/image/v2/D4D12AQFwZ9Fwkfbwsw/article-cover_image-shrink_600_2000/0/1683459137500

Martínez Pujol, S. (2022). Study of the aerodynamic behaviour of a Formula 1 front wing following the 2022 technical regulations [Bachelor's thesis, Universitat Politècnica de Catalunya]. https://upcommons.upc.edu/bitstream/handle/2117/372104/STUDY%20OF%20THE%20AERODYNAMIC%20BEHAVIOUR%20OF%20A%20FORMULA%201%20FRONT%20WING%20FOLLOWING%20THE%202022%20TECHNICAL%20REGULATIONS%20.pdf

McCabe, G. (2005). Explanation and discovery in aerodynamics. Studies in History and Philosophy of Modern Physics, 36(4), 685–703. https://doi.org/10.1016/j.shpsb.2005.08.004

Roberts, L. S. (2017). Boundary-layer transition on wings in ground effect [Ph.D. thesis, University of Southampton].

Singh, A., Choudhury, S., & Maiti, D. (2023). Multi-objective aerodynamic shape optimization of Formula SAE car using surrogate models and genetic algorithms. Journal of Mechanical Science and Technology, 37(1), 263–273. https://doi.org/10.1007/s12206-022-1224-6

Tienphuc, D., Zhengqi, G., & Zhen, C. (2016). Numerical simulation of the flow field around generic Formula One car model. SAE Technical Paper 2016-01-1590. https://doi.org/10.4271/2016-01-1590

Weingart, R. (2015). On-track testing as a validation method of computational fluid dynamic simulations of a Formula SAE vehicle [Master's thesis, California Polytechnic State University, San Luis Obispo].

Wikimedia Commons. (n.d.). 2023 6 Hours of Spa-Francorchamps [Photograph]. https://upload.wikimedia.org/wikipedia/commons/0/03/2023_6_Hours_of_Spa-Francorchamps_%28DSC04559%29.jpg